New Physics with IceCube

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Abstract

IceCube, a cubic kilometer neutrino telescope will be capable to probe neutrino-nucleon interactions in the ultrahigh energy regime, far beyond the energies reached by colliders. In this article we study an observable that combines several advantages. It only makes use of the upward neutrino flux so that the Earth filters the atmospheric muons, and it is just weakly dependent on the initial astrophysical flux uncertainties.

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I. INTRODUCTION

High precision or high energy are necessary to study the matter at short distances. The most powerful accelerators are the cosmic ones in the outer space. We know that the Earth is hit by cosmic rays of very high energy, which means that there have to be astrophysical mechanisms capable of accelerating protons to those high energies. It is then also possible that the same mechanisms could produce neutrinos of high energy or that the protons and radiation produced interact with matter to originate extremely high energy neutrinos. Some candidate neutrino sources are Active Galactic Nuclei (AGN) [1], which are the central regions of certain galaxies where the radiation emitted is comparable to the total radiation from the entire galaxy, and Gamma Ray Bursts (GRB) [2], that are the most powerful explosions since the Big Bang resulting usually from the core collapse of a massive star.

The integrated effect over all astrophysical sources in the sky where such producing mechanisms may operate, is expected to lead to a diffuse neutrino flux that could be detected by IceCube, which is planned to have a good directional resolution [3]. Another mechanism that contributes to a diffuse neutrino flux is given by the collisions of cosmic rays with the nucleons of the atmosphere. This flux is however negligible at the energies necessary to search for new physics effects. For energies above 10^5 GeV, the extraterrestrial diffuse flux should start to dominate over the atmospheric spectrum.

These high energy neutrinos coming from different sources can be used to search for new physics effects in neutrino-nucleon interactions using the nucleons of the Earth as targets. In order to bound such effects, the different observables that have been studied basically arise from comparing the surviving flux after passing through the Earth (which is strongly dependent on the neutrino-nucleon cross section) to the standard model prediction [4, 5, 6, 7].

II. OBSERVING NEW PHYSICS

In this work we define the observable $\alpha(E)$ in the following way. We consider only upward-going neutrinos, that is, neutrinos with arrival directions θ such that $0 < \theta < \pi/2$ and we denote by α the angle such that the number of events for $0 < \theta < \alpha$ equals the number of events for $\alpha < \theta < \pi/2$. Clearly, the value of α is energy dependent. For low energies, the cross section decreases and the Earth becomes transparent to neutrinos. In this case,

$\alpha \to \pi/3$ since for a diffuse isotropic flux this angle divides the hemisphere into two sectors with the same solid angle. Obviously for extremely high energies where most neutrinos are absorbed, $\alpha \to \pi/2$, and for intermediate energies, α varies accordingly between these limiting behaviors.

We will consider only the diffuse neutrino flux from extraterrestrial origin and assume that it is isotropic. The use of the observable $\alpha(E)$ reduces the effects of the experimental systematics and initial flux dependence. The functional form of $\alpha(E)$ sharply depends on the interaction cross section neutrino-nucleon. In this conditions, if physics beyond the standard model operates at these high energies, it will become manifest directly on the function $\alpha(E)$.

If we take into account a diffuse neutrino flux and for simplicity we consider it as not flat (an example is the given by the Waxman and Bacall [8]), then in a first analysis we can safely neglect the regeneration effects and approximate the Earth attenuation of the neutrino flux by [11],

$$\Phi(E,\theta) = \Phi_0(E) e^{\sigma_{\text{tot}}(E)\tau(\theta)}, \tag{1}$$

where $\tau(\theta)$ is the number of nucleons per unit area in the neutrino path through the Earth,

$$\tau(\theta) = N_A \int_0^{2R_{\text{E}}\cos\theta} \rho(z) dz. \tag{2}$$

Here $\Phi_0(E)$ is the initial neutrino flux, N_A is the Avogradro number, R_{E} is the radius of the Earth, and θ is the nadir angle taken from the downward-going normal to the neutrino telescope.

The number of events is given by the product of the corresponding integrated flux, the cross section, the density number, volume, acceptance, and the time interval of detection. As the definition of α is the equality between two number of events, all the previous factors cancel except the integrated fluxes at each side. Thus, α is defined by the equation

$$\int_0^{\alpha_{SM}(E)} d\theta \sin\theta e^{-\sigma^{SM}(E)\tau(\theta)} = \int_{\alpha_{SM}(E)}^{\pi/2} d\theta \sin\theta e^{-\sigma^{SM}(E)\tau(\theta)}. \tag{3}$$

We solve this equation numerically and the result is shown in Fig. 1. There we have considered the standard model cross section as it was calculated in [9] and for $\tau(\theta)$ we use Eq. 2 with the Earth density as given by the PREM [10].

Both the SM predictions for the total cross section and the Earth density have uncertainties that propagate to the observable $\alpha(E)$. In Fig. 3, where the new physics effects on $\alpha(E)$ are shown, the effects of the mentioned uncertainties of the observable are also included.

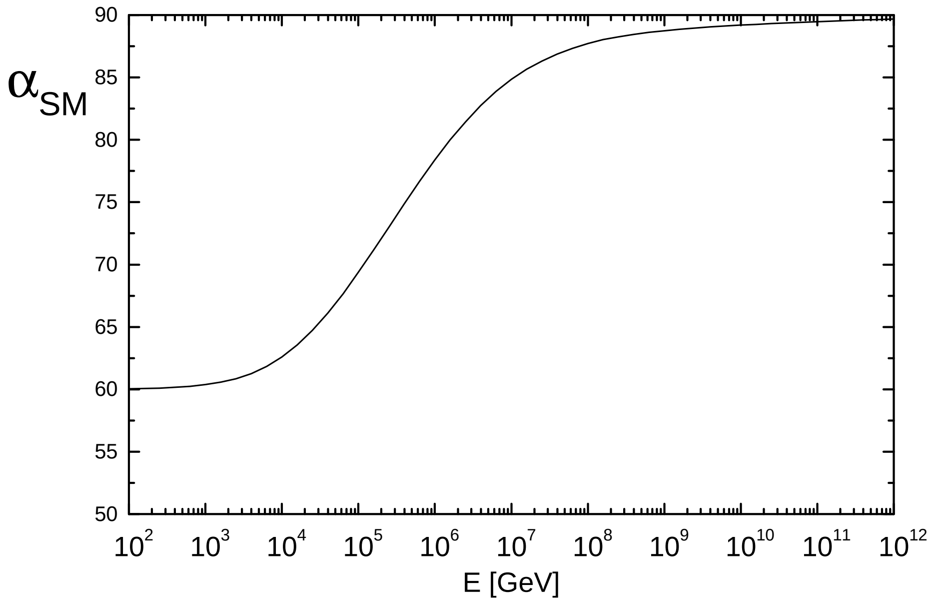

FIG. 1: Standard Model prediction for $\alpha_{SM}(E)$

To reduce background, one looks for upward moving muons produced when neutrinos coming from the opposite side of the Earth interact with the nucleons in their path. Directional reconstruction of these tracks suppresses the atmospheric muon backgrounds. By selecting the neutrino events that are up going it is possible to eliminate the atmospheric muons since they are downward-going.

III. FOUR-FERMION INTERACTIONS

In order to model in a general way the new physics effects on $\alpha(E)$ we consider a general 4-fermion interactions as given by an effective operator that includes the SM fields involved in the neutrino-nucleon scattering with left-handed neutrinos. If there are new interactions between quarks and leptons then the new effects should appear at an enough high energy. We call this characteristic energy scale for the new interactions Λ. At energies below Λ, these interactions are suppressed by an inverse power of Λ. Thus, the dominant effects should come from the lowest dimensional interactions with 4-fermions [12]:

$$\begin{aligned}\mathcal{L} = \mathcal{L}^{SM} + \frac{g_N^2}{2\Lambda^2}[&\eta_{LL}(\bar{l}\gamma_\mu P_L\nu\ \bar{q}_j\gamma^\mu P_L q_i + \bar{\nu}\gamma_\mu P_L\nu\ \bar{q}_i\gamma_\mu P_L q_i) + \\ &\eta_{LR}(\bar{l}\gamma_\mu P_L\nu\ \bar{q}_j\gamma^\mu P_R q_i + \bar{\nu}\gamma_\mu P_L\nu\ \bar{q}_i\gamma_\mu P_R q_i)]\end{aligned} \tag{4}$$

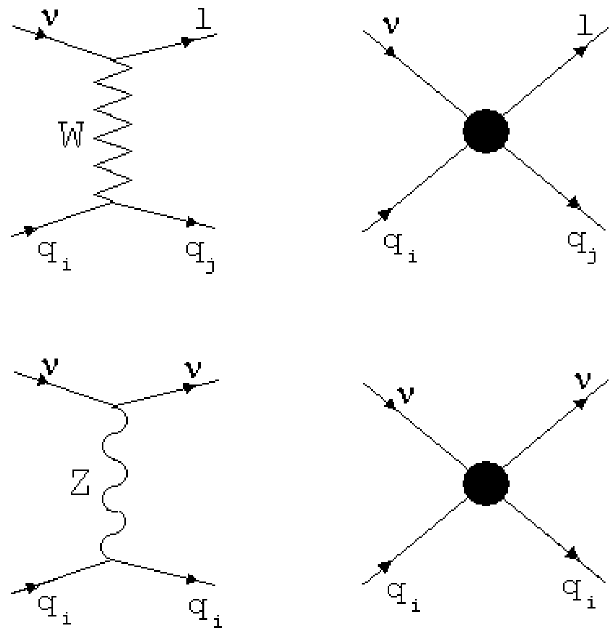

FIG. 2: Feynman diagrams contributing to charged current and neutral current process.

for left-handed neutrinos, where we take $g_N^2 = 4\pi$, while the coefficients η_{LL} and η_{LR} can take the values -1, 0 and 1. Choosing different values of Λ, η_{LL}, and η_{LR}, we can test the α observable on different scenarios of new physics.

Using the effective operator we can calculate their contribution to the neutrino-nucleon inclusive cross section.

$$\nu N \to \mu + \text{anything} \tag{5}$$

where $N \equiv \dfrac{n+p}{2}$ is an isoscalar nucleon. The corresponding processes are pictured in Fig. 2 for charged and neutral current. The calculation is standard and we use it to compare the results of [9]. For the charged current, the scattering amplitude is

$$\mathcal{M}^{CC} = -\frac{ig^2}{2(Q^2 + M_W^2)} \bar{l}\gamma_\mu P_L \nu \; \bar{q}_j \gamma^\mu (g_L^{'} P_L + g_R^{'} P_R) q_i, \tag{6}$$

where

$$
\begin{aligned}
g_L^{'} &= 1 - \frac{(Q^2 + M_W^2)}{\Lambda^2}\eta_{LL}\frac{g_N^2}{g^2} \\
\\
g_R^{'} &= -\frac{(Q^2 + M_W^2)}{\Lambda^2}\eta_{LR}\frac{g_N^2}{g^2}
\end{aligned}
\tag{7}
$$

include the new physics effects.

The differential cross section for charged currents reads

$$
\begin{aligned}
\frac{d\sigma^{CC}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\frac{M_W^2}{(Q^2 + M_W^2)}\right)^2 x[g_L^{'2}(Q^{CC} + (1-y)^2\bar{Q}^{CC}) \\
+ g_R^{'2}(\bar{Q}^{CC} + (1-y)^2 Q^{CC})]
\end{aligned}
\tag{8}
$$

where for an isoscalar target we have the quark distribution functions

$$
\begin{aligned}
Q^{CC}(x, Q^2) &= \frac{u_v(x, Q^2) + d_v(x, Q^2)}{2} + \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} \\
&\quad + s_s(x, Q^2) + b_s(x, Q^2) \\
\\
\bar{Q}^{CC}(x, Q^2) &= \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} + c_s(x, Q^2) + t_s(x, Q^2)
\end{aligned}
\tag{9}
$$

Similarly, the neutral current amplitude is

$$
\mathcal{M}^{NC} = -\frac{ig^2}{2c_W(Q^2 + M_Z^2)}\bar{\nu}\gamma_\mu P_L \nu\ \bar{q}_i\gamma^\mu(g_L^{'} P_L + g_R^{'} P_R)q_i, \tag{10}
$$

where $c_W = \cos\theta_W$ and

$$
\begin{aligned}
g_L^{'i} &= g_L^i - \frac{Q^2 + M_Z^2}{\Lambda^2}c_W^2\eta_{LL}\frac{g_{LL}^2}{g^2} \\
g_R^{'i} &= g_R^i - \frac{Q^2 + M_Z^2}{\Lambda^2}c_W^2\eta_{LR}\frac{g_{LR}^2}{g^2}
\end{aligned}
\tag{11}
$$

include the new physics effects. Here, $g_L^U = 1/2 - 2/3x_W$, $g_L^D = -1/2 + 1/3x_w$, $g_R^U = -2/3x_W$, and $g_R^D = 1/3x_W$.

The neutral current differential cross section is then

TABLE I: Sets of parameters for the new four- fermion contact interactions.

Set	η_{LL}	η_{LR}	Λ (TeV)
1	1	1	1
2	-1	-1	1
3	-1	-1	2
4	1	1	0.8
5	-1	-1	0.8

$$\begin{aligned}\frac{d\sigma^{NC}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\frac{M_Z^2}{(Q^2+M_Z^2)}\right)^2 \sum_{i=U,D} x[g_L^{`i2}(Q^i + (1-y)^2\bar{Q}^i) \\ + g_R^{`i2}(\bar{Q}^i + (1-y)^2 Q^i)],\end{aligned} \tag{12}$$

where the corresponding parton distributions for a isoscalar target read

$$\begin{aligned}
Q^U(x,Q^2) &= \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} \\
&\quad + c_s(x,Q^2) + t_s(x,Q^2) \\
Q^D(x,Q^2) &= \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} \\
&\quad + s_s(x,Q^2) + b_s(x,Q^2) \\
\bar{Q}^U(x,Q^2) &= \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + c_s(x,Q^2) + t_s(x,Q^2) \\
\bar{Q}^D(x,Q^2) &= \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + s_s(x,Q^2) + b_s(x,Q^2).
\end{aligned}$$

IV. RESULTS

In Fig. 3 we show our results for the α observable for the most representative sets of parameters and the standard model prediction including the theoretical uncertainties from the SM cross section and the Earth density. For the new physics effects we have considered the sets of parameters show in Table I.

In Fig. 4 we show the differences between the values of α for different sets of parameters and the standard model value as a function of the energy. It can be seen that the maximum sensitivity is reached in the intermediate energy range (10^5GeV $<$ E $<$ 10^7GeV).

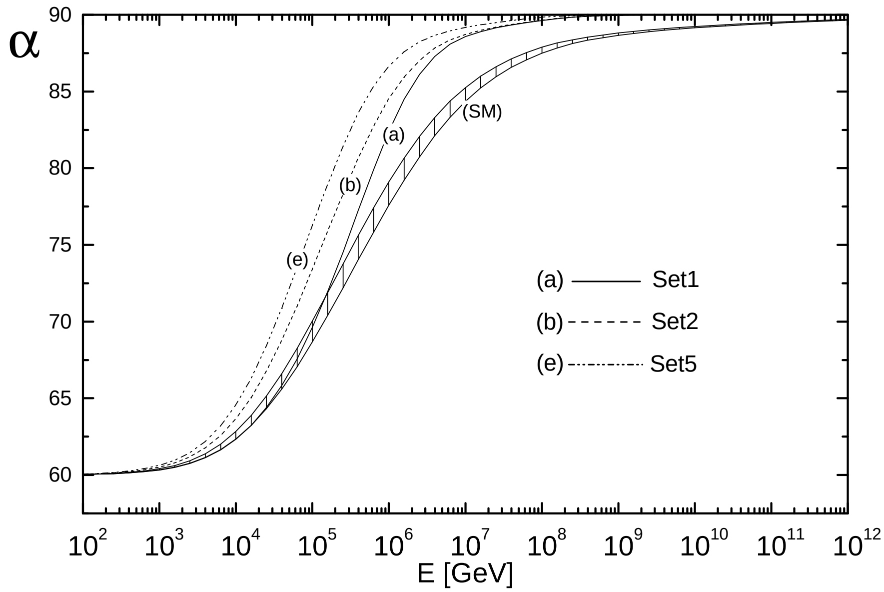

FIG. 3: $\alpha(E)$ for different sets of parameters: (a) set1, (b) set2, (e) set5 and the standard model prediction with the theoretical uncertainties includes.

In the same context, we can define another observable related to $\alpha_{SM}(E)$. We consider the hemisphere $0 < \theta < \pi/2$ divided into two regions by the angle α_{SM}, $\mathcal{R}_1$ for $0 < \theta < \alpha_{SM}$ and $\mathcal{R}_2$ for $\alpha_{SM} < \theta < \pi/2$. We then calculate the ratio χ between the number of events for each region,

$$\chi = \frac{N_1}{N_2}, \tag{13}$$

where N_1 is the number of events in the region $\mathcal{R}_1$ and N_2 the number of events in the region $\mathcal{R}_2$. By using χ the effects of experimental systematic and initial flux dependence are reduced.

If there is only standard model physics, then we have that the ratio $\chi = 1$. The new physics effects produce a deviation from the standard value as we show in Fig. 5 for the different sets of parameters (different values of Λ, η_{LL}, and η_{LR}).

V. CONCLUSIONS

In the present work we have studied a new observable that combines the survival neutrino flux after passing through the Earth in a way that reduces the experimental systematic and the dependence with the initial flux. This observable, the angle α, divides the up-going

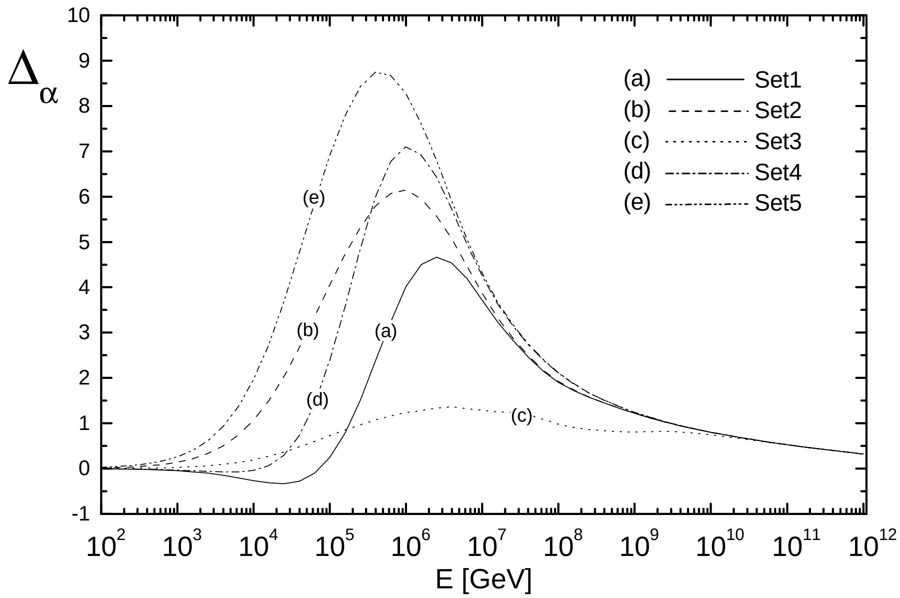

FIG. 4: Differences between α for different sets of parameters and the standard model prediction.

hemisphere (with respect the arrival neutrino directions) into two homo-event sectors and it is dependent, of course, on the neutrino energy. The function $\alpha(E)$ is sharply dependent on the neutrino-nucleon cross section, which makes it a useful observable to bound new physics. In order to test the sensitivity of α, we have calculated the new physics effects coming from four-fermion contact interactions. We also have studied as another observable, the ratio between the number of events in the regions defined by $\alpha_{SM}(E)$.

We note that the introduced observables present no deviation from the standard model prediction for low energies ($< 10^4$ GeV) at which almost no interactions occur with or without new physics. At high energies ($> 10^9$ GeV) the neutrino mean free path is so small that the integrated surviving flux of Earth skimming neutrinos equals the one corresponding to almost the whole hemisphere. The corresponding increase in the cross section implies that, given the exponential behavior of the integrated flux, a great attenuation takes place both taking into account new physics effects or not.

Finally, we point out that this technique can be applied to any specific case of physics beyond the standard model, which is left for future work.

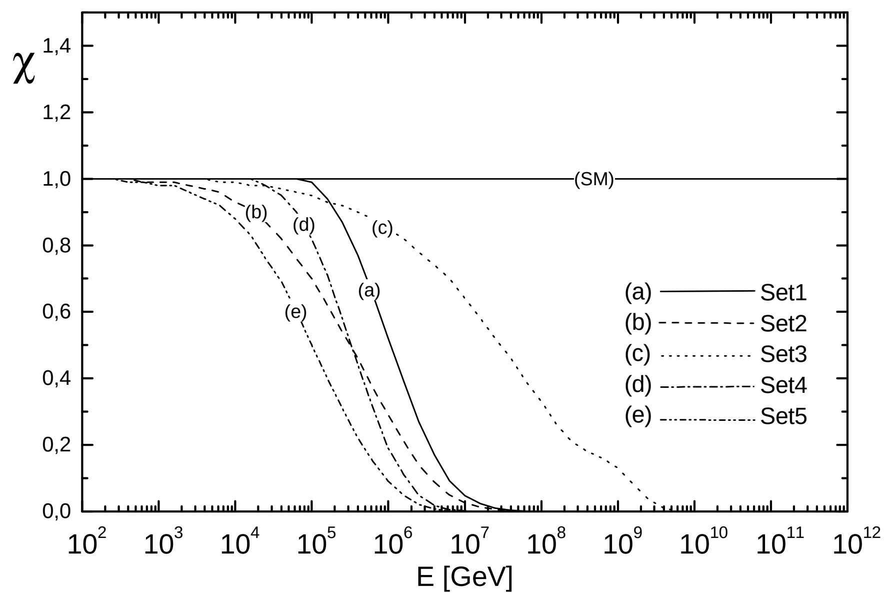

FIG. 5: Observable $\chi(E)$ for different sets of parameters.

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